

Investigation of the Energy-Based Approach in the Optimization of Viscous Dampers

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Abstract

This study presents an energy-based optimization framework for the simultaneous placement and parameter selection of fluid viscous dampers (FVDs) in steel moment-resisting frames. A modified binary-real particle swarm optimization (BRPSO) algorithm is employed to determine the optimal story-wise distribution of dampers together with their damping coefficients and velocity exponents. The objective is formulated in terms of the energy dissipated by the dampers relative to the seismic input energy, while an interstory drift limit is imposed as a structural constraint. Special steel moment-resisting frames with six and ten stories are modeled in OpenSees and analyzed under Kanai-Tajimi filtered white-noise base excitation. The numerical results show that the optimized damping configurations substantially reduce structural hysteretic energy. For the six-story frame, five optimally placed dampers reduce the hysteretic energy by 99.11% and the input energy by 12.12% relative to the uncontrolled frame. For the ten-story frame, eight dampers eliminate the accumulated hysteretic energy and reduce the input energy by 34.93%. Increasing the number of dampers beyond these configurations produces only marginal additional improvements in the objective measure and energy dissipation, indicating a diminishing-return effect. The results demonstrate that the proposed energy-based BRPSO framework can simultaneously identify effective damper locations and mechanical parameters while avoiding unnecessary installation of dampers at all stories.

Keywords

Fluid viscous damper; dynamic analysis; optimization of parameters and placement; energy-based approach; steel moment-resisting frame.

1. Introduction

Passive control devices are particularly attractive because they dissipate seismic energy without requiring an external power supply. Among these devices, fluid viscous dampers (FVDs) have been widely investigated because their response is related to the relative velocity across the device, allowing a significant portion of the input energy to be dissipated without substantially increasing the strength of the primary structural members [1–3]. Previous studies have examined the nonlinear behavior, parameter selection, placement, and multi-objective optimization of viscous dampers using different response measures, including interstory drift, acceleration, displacement, cost, and structural weight [2,4]. Energy-based measures have also been proposed as useful indicators for evaluating damper effectiveness because the partition of seismic input energy between structural hysteresis and supplemental damping is directly related to the development of inelastic response [2].

Despite these developments, the simultaneous optimization of the vertical distribution and mechanical parameters of viscous dampers using a unified energy-based criterion remains relatively limited, particularly for steel moment-resisting frames with different heights. In many existing approaches, damper locations and mechanical properties are selected separately or optimized using conventional response quantities. The present study addresses this gap by developing an

energy-based optimization framework in which damper placement, damping coefficient, and velocity exponent are determined simultaneously. The optimization is carried out for six- and ten-story special steel moment-resisting frames using a modified binary-real particle swarm optimization algorithm (BRPSO). The main contribution is the use of an energy-based objective to promote seismic-energy dissipation by the dampers while limiting interstory drift, thereby allowing effective performance to be achieved without installing dampers at all stories.

Fluid viscous damping is especially suitable for this type of formulation because the device transforms relative-motion demand into dissipated energy, while its force characteristics can be adjusted through a small set of mechanical parameters. Consequently, an energy-based objective can provide a common measure for comparing different damper layouts and parameter combinations without requiring the optimizer to rely on a single structural response quantity.

2. Methodology

Fluid viscous dampers dissipate seismic energy through the motion of a piston within a high-viscosity fluid. Relative motion between the two ends of the device drives fluid flow through the piston orifices and produces a resisting force that depends on the relative velocity. The mechanical response is governed primarily by the damping coefficient and the velocity

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exponent, which together control the magnitude and nonlinearity of the damping force [3]. These parameters therefore provide two important continuous design variables for optimization.

Particle swarm optimization (PSO) is a population-based metaheuristic inspired by collective behavior in nature. Each particle updates its position by using its own experience and information from the population, making the method suitable for nonlinear optimization with a relatively small number of control parameters [4,5]. In the present study, the binary and real-coded forms of PSO are combined to construct BRPSO. The binary component represents the presence or absence of a damper at each story, whereas the real-coded component represents the damping coefficient and velocity exponent of the selected dampers. This hybrid representation enables the placement and mechanical properties of the dampers to be optimized simultaneously.

Special six- and ten-story steel moment-resisting frames are modeled in OpenSees using nonlinear beam-column elements and concentrated plasticity at the member ends. The numerical models are first checked against previously published response data, and the comparison indicates good agreement for the principal response quantities. The optimized frames are then subjected to Kanai-Tajimi filtered white-noise base excitation. For each specified number of dampers, BRPSO searches for the best story distribution and corresponding damper parameters. The optimization objective is based on the ratio of seismic input energy to energy dissipated by the viscous dampers, while the maximum interstory drift is constrained to remain within the adopted allowable limit. Five independent optimization runs are performed for each damper-number configuration, and the solution with the lowest objective value is selected.

The modeling strategy is intentionally kept concise in the extended abstract. The damper component is represented as a velocity-dependent energy-dissipation device, and its principal variables are optimized within prescribed lower and upper bounds. The binary placement vector is linked directly to the corresponding real-coded parameter vector, so that each selected story is assigned a unique set of damping properties. This formulation avoids treating placement and parameter calibration as separate optimization stages and permits the algorithm to search for combinations that are efficient from an overall energy perspective. The numerical response of the frames is evaluated in the time domain, and the energy quantities are obtained consistently for the uncontrolled and controlled cases.

3. Discussion and Results

The BRPSO results show that damper number and placement have a pronounced effect on the energy distribution of the frames. As the number of dampers increases, the objective value decreases progressively up to a threshold, after which the improvement becomes comparatively small. For the six-story frame, the optimal practical configuration is obtained with five

dampers located at Stories 1, 2, 4, 5, and 6. Increasing the number from five to six produces only a small additional reduction in the objective value, indicating a limited performance gain relative to the additional device required. For the ten-story frame, eight dampers located at Stories 1, 2, 4, 5, 6, 7, 8, and 10 provide the most appropriate compromise between performance and the number of devices.

In the six-story frame, the five-damper configuration reduces the maximum input energy from 19,355 to 17,009 Kips·in., corresponding to a 12.12% reduction, while the hysteretic energy decreases from 10,642 to 95 Kips·in., corresponding to a 99.11% reduction. The energy dissipated by the dampers reaches 12,876 Kips·in. Figure 1 compares the energy dissipation at the plastic hinges of the six-story frame for the uncontrolled and optimized configurations. For the ten-story frame, the eight-damper configuration reduces the maximum input energy from 11,923 to 7,758 Kips·in., corresponding to a 34.93% reduction, while the hysteretic energy is reduced from 3,107 Kips·in. to approximately zero. The optimized dampers dissipate 5,354 Kips·in. of energy. Figure 2 compares the energy dissipation at the plastic hinges of the ten-story frame for the uncontrolled and optimized configurations.

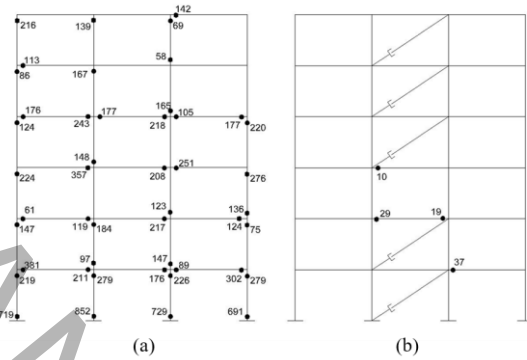


Figure 1. Comparison of hysteretic energy dissipation at each plastic hinge of the six-story frame: (a) without viscous dampers and (b) with optimized viscous dampers

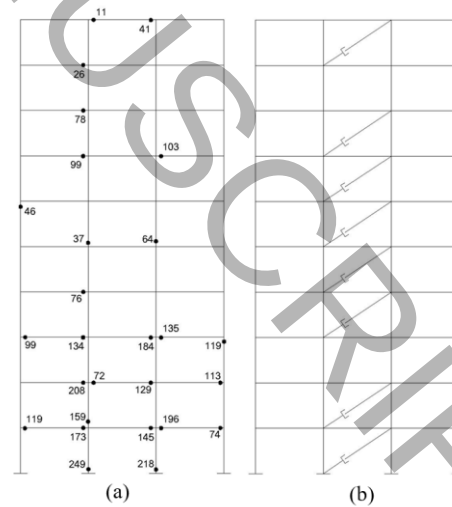


Figure 2. Comparison of hysteretic energy dissipation at each plastic hinge of the ten-story frame: (a) without viscous dampers and (b) with optimized viscous dampers

The comparison among different damper numbers also indicates a clear diminishing-return trend. In the six-story frame, the reduction in hysteretic energy changes only slightly when the number of dampers increases beyond five. Likewise, in the ten-story frame, the hysteretic energy has already reached zero with eight dampers and remains at zero for nine and ten dampers, while the additional increase in damper-dissipated energy is relatively small. The interstory-drift results show a substantial overall reduction for the optimized configurations. For the ten-story frame, however, localized increases in drift occur at some upper stories because the optimization criterion prioritizes energy dissipation rather than directly minimizing drift. This observation highlights the importance of defining the optimization objective according to the intended performance target. Overall, the results demonstrate that energy-based optimization can identify efficient damper layouts and avoid unnecessary installation of devices throughout the entire height of the structure.

The BRPSO results show that increasing the number of dampers reduces the objective value progressively up to a threshold, after which the improvement becomes marginal. For the six-story frame, the five-damper configuration is the practical optimum, while six dampers provide only a small additional improvement. For the ten-story frame, eight dampers are sufficient to eliminate the accumulated hysteretic energy; increasing the number to nine or ten does not reduce it further and provides only limited additional damper energy dissipation.

The optimized story patterns further illustrate that the most effective distribution is not necessarily uniform. In both frames, the selected dampers are concentrated at several stories rather than being installed at every level. The six-story solution activates five of the six stories, whereas the ten-story solution activates eight of the ten stories. This result is consistent with the energy-based objective: once a sufficient number of devices is available to divert most of the seismic energy away from structural hysteresis, adding more devices produces little additional benefit. The corresponding optimized damping coefficients and velocity exponents vary from story to story, confirming that a single uniform damper specification is not necessarily the most efficient solution.

From a structural-performance viewpoint, the optimized dampers substantially reduce the demand associated with plastic deformation. The comparison of plastic-hinge energy shows that most structural components remain within or close to the elastic range in the optimized configurations, particularly for the five-damper six-story and eight-damper ten-story cases. The interstory-drift comparisons also demonstrate a strong overall improvement, while revealing an important characteristic of the proposed objective: because energy dissipation is prioritized, local drift at some upper stories can increase slightly even when the global energy response improves. Therefore, the present framework is best interpreted as an energy-oriented

performance design procedure rather than a direct drift-minimization method.

The optimal configurations summarized in Table 1 avoid installing dampers at every story while maintaining substantial energy-dissipation capacity. The corresponding damper-dissipated energies are 12,876 Kips·in. for the five-damper six-story case and 5,354 Kips·in. for the eight-damper ten-story case.

Table 1. Summary of the optimal damper configurations and principal energy results

Frame	Optimal FVDs and stories	Input / hysteretic energy reduction	Damper-dissipated energy (Kips·in.)
6-story	5; 1, 2, 4, 5, 6	12.12% / 99.11%	12,876
10-story	8; 1, 2, 4, 5, 6, 7, 8, 10	34.93% / 100%	5,354

4. Conclusions

An energy-based framework was developed for the simultaneous optimization of viscous damper placement and mechanical parameters in six- and ten-story special steel moment-resisting frames. The BRPSO algorithm successfully combines binary placement variables with continuous damper parameters and identifies effective configurations under an interstory-drift constraint. The results show that five dampers are sufficient for the six-story frame and eight dampers for the ten-story frame to obtain nearly complete or complete suppression of structural hysteretic energy. Increasing the number of dampers beyond these practical configurations provides only marginal additional benefits while increasing the required equipment and construction cost. Therefore, the proposed framework provides a rational basis for performance-oriented damper design in which seismic energy is intentionally redirected from the primary structural system to supplemental damping devices. The approach can be extended to three-dimensional frames and to suites of real earthquake records, including near-fault and far-fault ground motions.

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